Sludge drying reed beds: a full and pilot-scales study for activated sludge treatment

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Abstract Sludge drying reed beds have been used for dewatering and mineralization of sludge since the beginning of the 90's, but their insufficient performances in terms of Dry Matter [DM] content and mineralization of the sludge have made necessary new studies. Therefore, 8 pilots of 2m² each and a full-scale plant (13 000 p.e , 8 beds of 470m² in operation for 4 years) have been monitored to examine the influence of the sludge loading rate, the sludge quality and the loading frequency on the dewatering and mineralization efficiencies. Two filtration layers (vegetal compost or sand) and two loading rhythms were tested on pilots which were fed at a loading rate of 25 kgDM.m^{-2}.yr^{-1} during the first year of operation (commissioning period). Hydraulic behaviour (infiltration rate, outflow), O_2 and CO_2 relative concentrations in the filtration media, redox potential, pollutants removal and dry matter content were assessed during all the study. The rheological quality of the extracted sludge from full scale beds were assessed and showed that it mechanical behaviour exceed those of sludge of comparable dry matter content, making its spreading easier Therefore, these sludge could easily claim the status of solid and stabilized sludge according to the French regulation. Design and management recommendations (number of beds, loading rates, feeding/rest period) gained from the experiments results are suggested.
Keywords activated sludge, sludge drying, reed beds, dewatering, rheology characteristics

INTRODUCTION

Sludge drying reed beds (SDRB) for WWTP sludge dewatering and mineralization exist in France since the early 1990s and have been relatively successful over the last ten years because approximately 300 systems have been built in France with a treatment capacity between 200-12 000 people equivalent [P.E.] (Lesavre, 2002) whereas the last which have been built are sized for 26 000P.E.
It is admitted that reduction of the amount of sludge occurs in SDRBs (Burgoon *et al.*, 1997; Hofmann, 1990; Liénard, 1999; Liénard *et al.*, 1995; Nielsen, 2003; 2005; Obarska-Pempkowiak *et al.*, 2003) both with dewatering (drainage and evapotranspiration) and aerobic mineralization. The sizing of SDRBs is roughly based on the sludge production, its quality and the organic load acceptance (Nielsen, 2003). Several investigations have been done on dewatering and mineralization efficiencies of SDRBs used for activated WWTP (Barbieri *et al.*, 2003; Begg *et al.*, 2001; Liénard, 1999; Liénard *et al.*, 1995; Mellstrom and Jager, 1994; Nielsen, 2003; 2005) where a general design of 50-60 kgDM.m^{-2}.yr^{-1} (Liénard, 1999; Mellstrom and Jager, 1994; Nielsen, 2003) with a half load (25 kgDM.m^{-2}.yr^{-1}) during the commissioning period is recommended. The system consists in several beds constructed in parallel and alternately fed which allowed sufficient rest period for dewatering and progressive mineralization of the sludge deposit. Nevertheless, only a few studies concern either the influence of the number of beds or its design on the dewatering and mineralization performances. (Liénard, 1999) pointed out that with 4 beds, each being alternately fed during a week and running at full capacity, the dewatering efficiency should not exceed a dry matter (DM) content of 15% whereas in Denmark, (Nielsen, 2003; 2005) observed a DM content up to 30-40% with 8 or more units.

The ignorance of the concerned mechanisms tend to empiricism and uncertainties in bed design (number of beds, composition of the filtration layer, passive aeration design,…) and operational strategy (organic load, hydraulic load, feeding/rest periods,…) which can lead to anaerobic conditions and poor vegetation growth (essentially during the commissioning phase), insufficient drainage and clogging phenomenon (Nielsen, 2003; 2005). In this context, this work undertook new investigations on pilots and full scale SDRBs, to define more precisely these key parameters and thus to increase the performance of SDRBs and point out the feasibility of sludge spreading by the determination of its rheological characteristics.

METHODS AND MATERIALS

The pilot-scale beds

The experiments were performed on 8 experimental concrete beds of 2m^2 each built close to an extended aeration activated sludge plant (Andancette, 13 000 PE, France) (see **Figure**). 9 clumps.m^{-2} of one year old *Phragmites australis* plantlets were planted in May 2006. The pilots only differ in the top filtration layer to test the importance of capillary connection on water drainage. We used 5 cm of sand (d10=0.35, UC=3.2) or 10 cm of green compost from a composting platform according to the French standard NF U 44-051. Six pilots are fed exclusively with aerated sludge (from the WWTP aeration tank) while two others are fed with the thickened aerated sludge to verify if a lower hydraulic rate with the same solids content could achieve a better dewatering efficiency.
Therefore, activated sludge from aeration tank is pumped in a static thickener with a for 4 to 24 hours before being extracted to the concerned pilots.
Pilot design and loading characteristics are presented in Figure and Figure .
During the first half-year after planting, the pilots were fed with treated wastewater for a good acclimatization of the reeds. After that a commissioning period of 1.5 year started in January 2007 with a specific-loading rate of 30kgSS.m^{-2}.yr^{-1} for all the pilots in order to ensure a good reed establishment (reed density of at least 250 stems.m^{-2}).
Two feeding frequencies were tested for the pilots fed with the septage/activated sludge mixture which simulate a configuration of 6 and 10 drying reed beds in parallel. Feeding and rest ratios are summarized in Table 3.

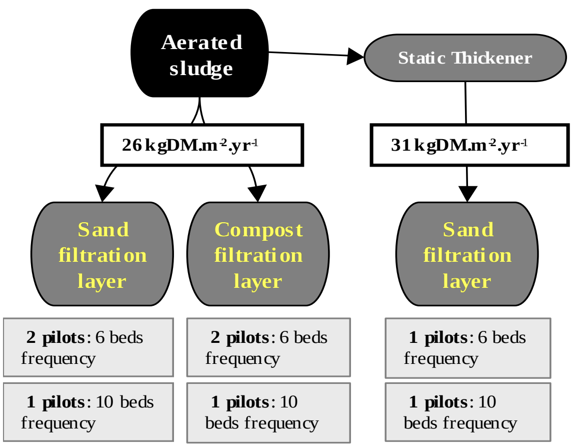

Figure 2: Top filtration layer, feeding strategy and organic loads applied on the pilots during the commissioning period

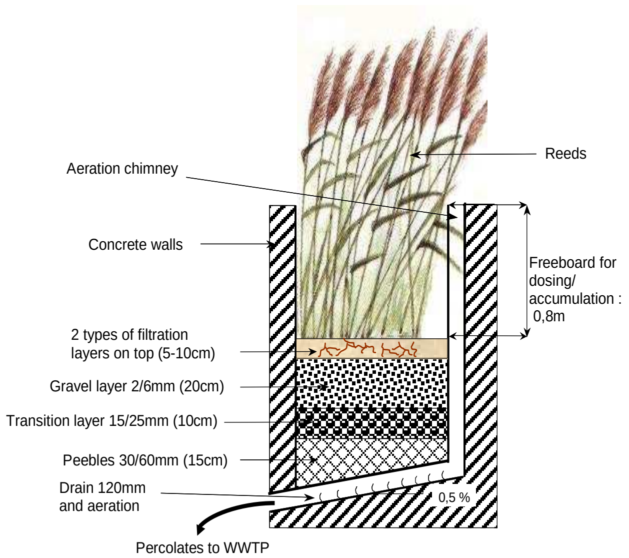

Figure 1
: Cross section of a pilot plant

The full-scale beds

The performances of the sludge drying reed bed system in Andancette (France) were also monitored. It is the second largest facility in France which was built in 2003 by SINT for a 13000 P.E. activated sludge in extended aeration activated sludge wastewater treatment plant. The reed beds have a capacity of approximately 314T DM per year.

The sludge drying reed beds were established and planted with reeds in July 2003 and consists of 8 square beds, each having an area of $468m^2$ at the filter surface and a maximum area loading rate of $80kgDM.m^{-2}.yr^{-1}$. The beds are fed by a pump, placed directly in the aeration tank, with a $130m^3.h^{-1}$ ($0.28m^3.m^{-2}.h^{-1}$) flow dispatched in four feeding points, to ensure a uniform distribution of the sludge. The outflow of leachate from the beds returns directly to the head of the WWTP.

The bed design is identical than this presented Figure with a 10 cm top filtration layer of vegetal compost. The passive aeration system consists of 9 drain pipes (every 2 m approximately) which collect the leachate in the bottom layer and are connected to the atmosphere on opposite sides.

As the WWTP is actually half-loaded, it was possible to feed some beds at different organic loads which are summarized in Table 1.

Since 2007, each bed was fed with a loading period of 2 weeks followed by 14 weeks of rest.

Three reed beds have been monitored with the following loading and oxygenation strategies:

- Two beds (E and F) at approx. 40kg $DM.m^{-2}.yr^{-1}$ which differ only by their aeration system (one pipe over two was obstructed on bed F).
- One bed (G) with a load about 30kg $DM.m^{-2}.yr^{-1}$ and aeration system opened.

Table 1: Characteristics of the monitored full-scale beds

Bed name	Feeding/rest (week)	Loading rate * (kgSS.m-2.yr-1)	Loading rate 2007 (kgSS.m-2.yr-1)	Sludge height (cm)	Reed density **
E		36	44	40	180
F	2/14	36	37	40	210
G		30	25	20	-

*global loading rate applied after the commissioning period which ended in 2005

** mean density measured at the end of spring (June-2007)

Sludge sampling. Figure 1 shows a high spatial heterogeneity (vertical and horizontal) of the dry matter content of the residual sludge over the whole reed bed surface and at three depths on bed G. The results do not present any logical distribution for DM in regard of the feeding points nor a possible "side effect". Similar results have been observed also for organic matter (not presented here). Therefore with aim of doing a representative samples, a statistical analysis allowed to choose a minimum of 4 samples per bed at two depths (top and bottom) to obtain a 25% and 8% relative precision for DM and organic matter respectively.

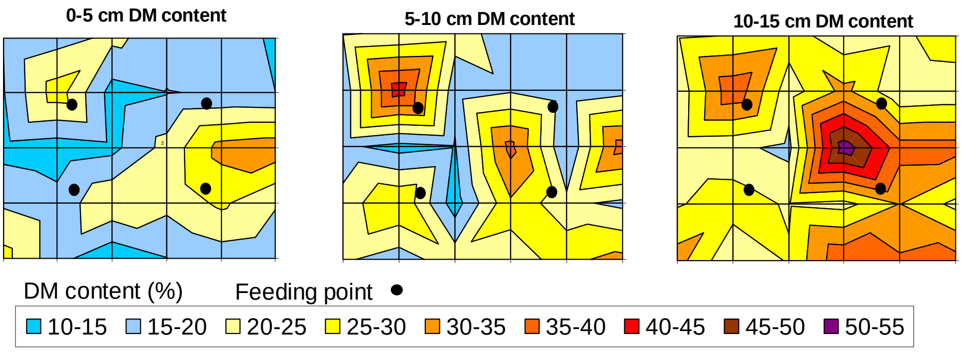

Figure 1: Top view of a reed bed surface heterogeneity for DM at 3 different depths (results of 90 samples done in May 2006)

During all the study two different sludge layers representing each the half of the depth of the sludge deposit have been distinguished:

- at the top; a fresh and poorly mineralized sludge with a pasty aspect
- at the bottom, a structured and well mineralized sludge

Chemical measurements

The percolation flow quality was assessed on pilots only the last day of a feeding cycle (except for SS which were measured every loading day) with a representative sample taken 24h after the feeding while a spot sample of the influent sludge is done during the feeding. COD, SS, KN, NH_4-N, NO_3-N, TP and PO_4-P were analysed according to the French standard methods (AFNOR, 2005a). The removal rates are calculated in flux ($[C_{in}*V_{in}-C_{out}*V_{out}]/[C_{in}*V_{in}]$)

Hydraulic measurements

Inlet flows were calculated with the time of functioning of the feeding pump whereas the outlet flow of the pilots are measured by the level of drained water through a pressure probe (STS) in a given adjacent vessel. For the full-scale beds an open channel and a rectangular weir (French standard NF X10-311) connected to a bubble flowmeter (ISCO 4230) are used. Infiltration rates (IR) were quantified by measuring the level of temporary excess surface water level with ultrasounds probes.

Dewaterability

The dewaterability of the activated sludge was determined through Capillary Suction Time (CST) and bound water measurements. The CST has been widely accepted and used for the evaluation of dewaterability of the sludge (Huisman and Van Kesteren, 1998). It measures the time in seconds necessary for the interstitial water to migrate by capillary suction from one point to another one at a standard distance on a specific filter paper. A high value of CST usually denotes a poor filterability and dewaterability. These measures were done by a Triton Electronics Ltd.© 304 M apparatus (10mm cylinder well).
The bound water measurement have been done thanks to a thermo balance (Kern MRS120-3) used at 105 °C and 10-20 % of humidity. The water distribution can be derived from the curve of the drying rate in relation to the moisture content of the sample (Kopp and Dichtl, 2001).

Quality of the sludge deposits

The *dry and organic matter* measurements have been done at 105°C and 550°C during 24h (to constant mass) and 2h respectively.
Aerobic conditions into the sludge were assessed by a redox measurements with a set for soil (Eijkelkamp, 18.28.SC). The measured values are converted according to the standard hydrogen electrode (SHE).
Once a week, 0_2, CO_2 and CH_4 measurements were made by a Dräger X am 7000 sensor just under the filtration layer to follow the respective concentration percentages of these gases in the gravel layer.
Sludge humification and its grade of stabilization were assessed by several indicators like the organic matter (loss of ignition), the biologic stability indicator (BSI) and biochemical organic matter characterization (BMC). These two last indicators give the organic matter percentage which could resist to mineralization when spread on land. (AFNOR, 2005b). Therefore, the residual sludge has been sampled in the bottom layer (15-30cm depth) of the sludge deposit at 6 different points in beds n°F and n°G in May 2008 (3-4 years old sludge) after 100 and 86 days of rest respectively.
Mechanical quality The mechanical quality was assessed by rheological measurements on a mixture of the bottom and top layer of sludge sampled on bed F after 97 days of rest at the end

of August 2007. The experiments consist in the study of the deformation and flow of sludge under the influence of an applied stress. This characterisation consists in the determination of:

- the yield stress, which define the rate of flow of the material. The yield stress was measured by the “slump test” (Baudez *et al.*, 2002),
- the adhesion power to assess the sticky behaviour of the sludge in the manure spreaders. A texture analyser TA 500 Lyod Instruments was therefore used.
- The compressibility of the material resulting to its rigidity and elasticity modulus.
- The interior friction angle (tan φ) and cohesion (C) which are determined from the shear stress at the breaking point (σ) resulting from different normal forces (Fn) applied on a shearing box (Figure 2):

$$\sigma = F_n.\tan(\varphi) + C$$

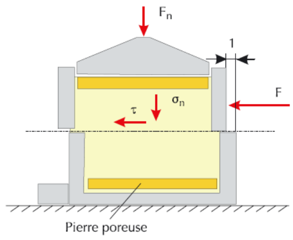

Figure 2: Casagrande box

RESULTS AND DISCUSSION

Influent sludge quality

The treatment plant is underloaded (50% of its full capacity in 2007) which explains the low suspended solids (SS) concentration (about 2%) of the activated sludge in the aeration tank taken to feed the full-scale beds and 6 over 8 pilots,2 others being fed with thickened sludge.
The static thickener allows a solid thickening factor of about 5. Besides, the activated thickened sludge dewaterability quantified by the CST and bound water percentage, is lightly higher than the one of the raw activated. This can be explained by the fact that the majority of its free water was evacuated after decantation and/or modification of the flocs structure induced by anaerobic conditions.

Table 2: Physico-chemical characteristics of the activated and thickened sludge (Jan 07 – May 08)

	Activated sludge			**Activated thickened sludge**		
Parameters	Average	SD*	Nb.of values	Average	SD*	Nb.of values
CST (sec)	7,1	1,7	55	9,7	3,3	93
Bound water (%)	20%	3%	4	30%	12%	12
pH	7,1	0,2	9	6,7	0,2	19
Cond (µS.cm-1)	1 063	131	10	1 174	159	20
DM (mg/l)	2 235	300	64	9 493	4087	116
SS (mg/l)	1 671	311	62	8 890	4114	110
VSS (%)	79	5	6	80	4	11
COD (mg/l)	1 908	263	11	11 840	4308	23
N-KNt (mg/l)	117	14	11	739	256	23
N-NH4+ (mg/l)	1,5	1,9	10	14,6	9,5	23
N-NO3 (mg/l)	0,4	0,2	5	0,3	0,2	4
P-PO4 3- (mg/l)	9,4	2,3	4	38,0	14,1	8
TP (mg/l)	39	12	6	229	80	13

* Standard deviation

Sludge dose and accumulation

Sludge accumulation rate for activated sludge is equivalent whatever is the filtration media or the feeding frequency simulated. Similar figures were observed in the literature with a $10cm.yr^{-1}$, $50kgDM.m^{-2}.yr^{-1}$ and 8 units running at their full capacity (Nielsen, 2005).

As presented in Table 3, for a same organic load but a lower hydraulic load, a higher accumulation rate was observed in the pilots fed with the thickened sludge. They also show signs of a poor dewatering and clogging especially for the 6 beds feeding frequency.

Table 3: Loading strategy and performances of the pilots units during the commissioning period

Sludge	Filtration layer	Nb. of beds simulation	Feeding/ rest period (d/d)	Hydraulic load * (cm.d^{-1})	Loading rate (kgDM.m^{-2}.yr^{-1})	Acc. rate (cm.yr^{-1})	Drainage outflow** (L.min^{-1}.m^{-2}) winter (7±5°C)	summer (19±3°C)	Outlet vol. in 12h* (%)
Activated	Compost	6	3.5/17.5	24±6	28	5.1±0.6	4.6	4.1	81±15
		10	3.5/31.5	31±9	27	5.3	3.8	6.2	64±16
	Sand	6	3.5/17.5	24±6	27	6.1±0.6	2.3	3.2	81±18
		10	3.5/31.5	31±9	26	5.4	2.8	5.1	64±16
Thickened	Sand	6	3.5/17.5	7±4	31	19.6	0.2	0.5	48±22
		10	3.5/31.5	8±4	32	9.3	0.2	0.3	51±23

* compared to the volume of the feeding dose
**mean of the peak outflow measured the last day of the feeding cycle

Plant growth

The main objective of the commissioning period is to ensure an initial good reed cover for the durability of the system. In fact, the reed growth may be compromised by: i) the sludge quality, ii) an inadequate organic or hydraulic load, iii) a non-optimised feeding and rest period ratio.
Nevertheless, in July 2007 on all pilots, the reeds showed signs of wilting due to a lack of water deficit because the amount of sludge was not sufficient to provide enough water. Therefore the pilots have been saturated with treated WW until 5 cm under the filtration layer during 20 days. This operation allowed the reeds to recover their vitality in 3 weeks.
In order to limit the wilting on the 10 beds frequency, we have shortened its cycle length from 35 to 20 days by decreasing the feeding period to 2 days during four months (Jul 07 – Nov 07).
The experimental set up has permitted to assess the influence of the feeding frequency, the growth media and the sludge quality (activated thickened or not) on the reed growth.

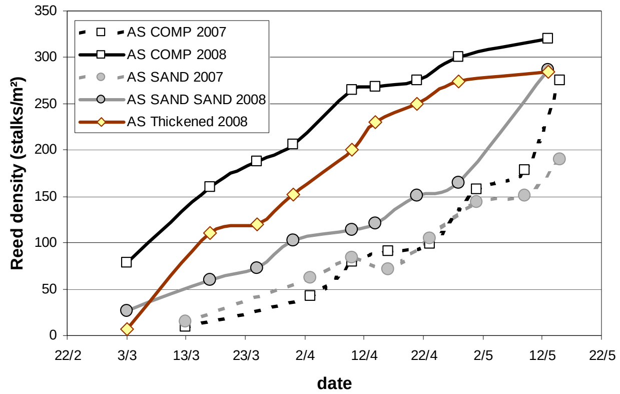

Figure 3: Reed density evolution in 2007 vs 2008 on pilots fed (AS: Activated Sludge, COMP: Compost filtration layer)

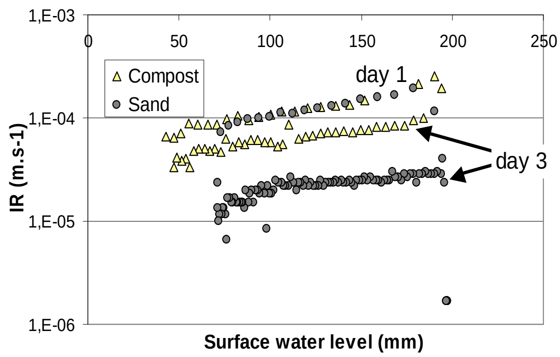

Figure 4: Infiltration rate with activated sludge in winter (Dec. 2007) on both filtration media

The following observations can be pointed out:

- The sludge quality did not impact negatively the reed growth even if some earlier wilting signs were observed the first year on pilots fed with thickened sludge
- A maximum of 3 and 2 days feeding period followed by maximum 20 days of rest is recommended for a 6 and 10 beds configuration respectively to avoid wilting of the reeds,
- The vegetal compost layer ensures a better growing media (Figure 3) and may improve capillary connection with the residual sludge compared to sand.

Dewatering efficiencies / sludge quality

Pilots results. The majority of the loaded volume is drained within 12 hours after feeding (see Table 3). For both filtration media the drainage efficiencies are quite similar in summer while they are better on compost during winter and activated sludge feeding.

We have observed similar infiltration rates on both filtration media during the first feeding day while the sand one led rapidly to clogging after the third day of feeding (Figure 4). The sludge deposit accumulated during the first feeding does not drive totally the hydrodynamic as the type of filtration media seems to play also a significant role. This is partly due to a better sludge porosity with compost due to a higher reed density and/or a better capillary connection between the sludge deposit and the filtration media.

The drying efficiencies (end of the rest period) are:

- Slightly depending of the filtration media
- Not improved with a 10 beds feeding frequency (not presented here) at a 3.5/31.5 feeding/rest ratio.
- Impacted by the weather conditions while the deposit is thin either by the temperature, freeze and thawing or by rainfall (Figure 5)
- Lower with thickened sludge than activated sludge alone

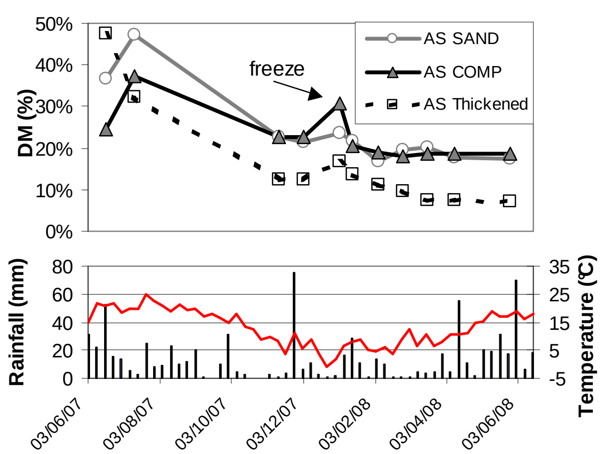

Figure 5: Dry matter content evolution in the sludge deposit in pilots (AS=Activated sludge, COMP=compost)

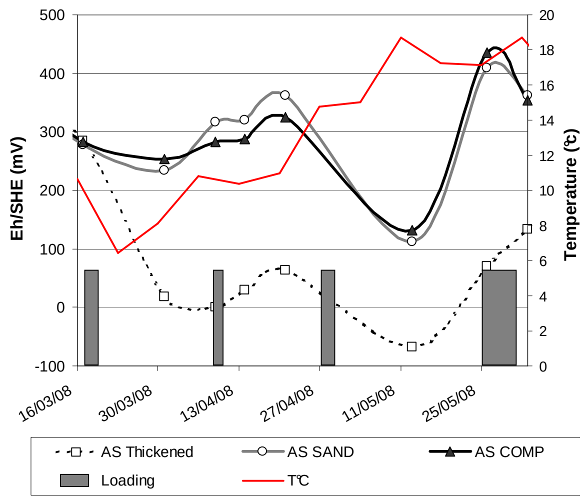

Figure 6: Redox potential variations in residual sludge in the pilots beds fed with thickened activated sludge or not

The low dewatering efficiencies on pilots fed with thickened sludge lead to anaerobic conditions within the sludge deposit (where the redox potential does not reach 200mV/SHE) despite good oxygen concentration in the air at the bottom of the beds (19,5 ±0,6 O_2%). Moreover, when air temperature increases in spring, the biological activity is stimulated resulting in an increase of oxygen demand and ORP (oxidation-reduction potential) drops down. When the easily degradable organic matter is mineralised the ORP goes up again (15-May).

Full-scale results. We have observed after a feeding cycle that the water which can be quickly drained by gravity (78±12% of the loaded volume is drained within the 24h with a mean outflow of 1.4±0.6L.min^{-1}.m^{-2}) allowed a dry matter content of approx. 8±4% in the top layer of the sludge deposit. This latter DM content will further increase by evapotranspiration.

The beds which received the highest loads (E and F) have reached a mean value of 30%DM in the top layer at the end of the summer (2007) while an average of 17 % DM is observed in winter. The benefits of freezing and thawing are clearly pointed out in January when the top layer reached 22%DM. Besides, the high standard deviations on the Figure 7 are due the high spatial heterogeneity of DM on the filter surface (Figure 1).

Humification. The humification performances have been essentially investigated on the full-scale beds. The organic matter decomposition takes place principally in the ten centimeters under the sludge surface. Figure 8 shows the ORP decrease in the top layer (0-15cm) due to the oxygen demand by the biological activity which corresponds also with a CO2 production which can be detected in the porosity of the filter media. The bottom layers of sludge are less impacted because better mineralised and structured by the rhizosphere activity.

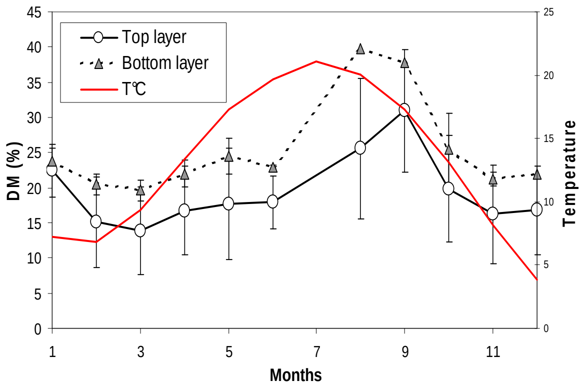

Figure 7: Mean evolution of the DM content on bed E and F over one year.

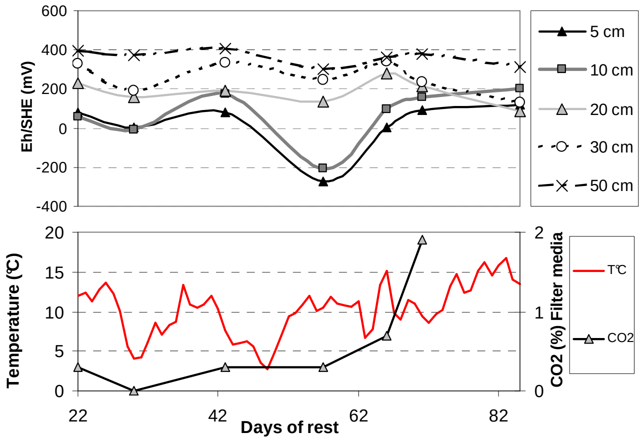

Figure 8: ORP in the sludge deposit at different depth under the sludge surface

The organic matter in the bottom layer of the sludge does not evolve anymore (4 years old sludge) and has reached a value of about 60%(DM). This indicates that approximately 25% of organic matter loaded was decomposed in CO_2, H_2O and minerals .
The high BSI and BMC values (92 and 46% respectively) indicate a good stability of this product close to vegetal compost and its land valorisation will give approximately 120kg of humus per ton.
On the other hand the two different aeration pipes density tested on the beds E and F did not show significative influence on the sludge mineralization (ORP evolution in the sludge deposit, mineralization kinetics) as the oxygen evolution in the filter media was similar for both configurations.

Quality of the leachates

The quality of the leachates from the pilots is relatively good as shown in Table 4 and in accordance with other experiments. Performances are lightly better with sand than with compost, but we have seen that this latter gave a higher density of reeds and a better drainage So, we would recommend a compost filtration layer which is less difficult to find than a sand with an adequate granulometry. Moreover, the leachate of the full-scale beds, with a compost filtration layer is clearly better (8,5mg L^{-1}.and 45mg.L^{-1} for SS and DCO_t respectively). The higher thickness of the sludge residue improves the filtration. Here also, the treatment of the thickened sludge does not present any advantage.

Table 4: Percolate contents and removal performances for pilots (commissioning period)

	Activated sludge (6&10beds)							Thickened sludge (6beds)			
	Compost filtration			Sand filtration				Sand filtration			
	Mean	SD	η*(%)	Mean	SD	η(%)	nb val.	Mean	SD	η (%)	nb val.
pH	7.5	0.2		7.6	0.2		23	7.5	0.1		9
Cond (µS.cm-1)	1213	166		1163	156		25	1448	287		10
SS (mg/l)	73	92	95.9	27	36	98.5	174	41	25	99.5	59
COD (mg/l)	105	89	95.4	64	20	96.8	29	136	62	98.1	11
N-KNt (mg/l)	6.7	6.3	94.7	7.7	7.2	92.3	29	13.5	12.9	96.4	11
N-NH4+ (mg/l)	1.8	2.1		4.8	6.0		29	9.8	15.0		11
N-NO3 (mg/l)	13.7	8.1		10.1	5.0		29	50.4	41.6		11
P-PO4 3- (mg/l)	11.2	2.0		12.3	2.6		9	24.9	4.3		4
PT (mg/l)	13.7	2.3		13.7	2.8		24	28.9	5.0		9

* removal rate

Mechanical quality of the sludge: an interesting material for land spreading?

The results from rheology characterisation of the sludge deposit are presented in Table 5. Despite a relatively low DM content (19%), the sample analysed from bed n°F exhibit a high yield stress (approx 3200 Pa) closed to a limed sludge (with higher DM content) while a pasty sludge with a similar DM content, has generally a yield stress ranged between 100 and 500 Pa according to their organic matter content. Concerning the compressibility, the analysed sample has a "spring constant" of 4200 $N.m^{-}1$ whereas a sludge dosed with 5% of lime (pasty aspect) and 20% DM (solid aspect) have a spring constant of 220 $N.m^{-1}$ and 7500 $N.m^{-1}$ respectively. Moreover the texture meter analysis showed that the sludge from reed beds is absolutely not sticking.

Finally, the low value of cohesion and interior friction angle proves that this sludge is sensible to shearing andcould be classified between values of a dry compost (3 kPa and tan(φ)=0.3) and manure (23 kPa and tan(φ)=0).

Table 5: Sludge rheological characteristics from bed F in August 2007

DM (% wet weight)	VS (% DM)	Yield stress–Slump-test (Pa)	Elasticity modulus (Pa)	Spring constant (N.m-1)	Cohesion (kPa)	Interior friction angle (tan φ)
19,4	62,9	3225	447	4257	1,09	0,0489

Due to rhizosphere effect, this residual sludge is comparable to a low deformable and well-structured material easy to spread on agricultural land.

The status of solid and stabilized sludge could be claimed for this sludge and according to the French regulation it can be extracted from the reed beds and temporarily stored on plots near the fields where it will be further spread if the harvest is not already done. The dissociation of emptying and spreading should give more flexibility to respect the ideal period to empty the bed(s) which must be scheduled between July 15th and late August to benefit both of the high evapotranspiration in summer and not to undermine the regrowth of reeds in the beds emptied before winter.

CONCLUSION

Experience gained from experiments conducted on pilots and full-scale sludge drying reed beds can be summarized in the following conclusions:

1. In the pilots, a density of planting of 9 clumps/m² enabled a good reed cover after the second growing season (>250 stems.m^{-2}) with a specific load limited to 25-30kgDM.m^{-2}.yr^{-1}.
2. Despite lower removal efficiencies during the commissioning period, a compost filtration layer is preferable compared to a sand because i) it ensures a better reed growing rate and, ii) it seems to optimize the capillary connection with the sludge deposits iii) physical filtration will further be improved when the height of the sludge deposits will increase with time.
3. Feeding with a thickened activated sludge on a sand filtration layer lead to low drainage, poor dewatering (even after 30 days of rest) even with 30 kgDM.m^{-2}.yr^{-1} of specific load. Moreover, there is no interest to complicate the process with thickening activated sludge before applying it on SDRBs.
4. An aeration pipe every 4 m does not reduce the oxygen content measured in the porosity of the filter media compared to another one every 2m.
5. The decomposition of the organic matter and its humification in the rhizosphere by the roots/microbial activities have led to an uncommon mechanical quality of the sludge despite its relatively low DM content. These characteristics make its land spreading easier than sludge with similar DM content.

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